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ARL-TR-2398

February 2001

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5069

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Fire Blankets for Munition Protection: Flame and Heat Blocking Properties of Advanced Materials

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Abstract

This report examines the flame and heat penetration through layers of fabrics as blankets for thermally protecting stored munitions. Evaluated were 27 fabrics made of inorganic fibers (alumina, silica, and ceramic fibers) and organic fibers (Kevlar, Nomex, and carbon) varying in thickness from 3 to 25 mm.

Two types of tests were performed. First, flame penetration tests were performed with an oxyacetylene flame. Visual observations and measured char depth into a wooden block at the back of the sample were used in the analysis. Second, heat penetration tests were performed in the heat penetration apparatus. A radiant heater was used for heat exposure. Temperatures were measured at the front and back surfaces of the inorganic fabrics and in each layer of the Kevlar fabric. The average steady-state temperatures were used for the analysis.

Effective thermal diffusivity values for the sample "blankets" were estimated from the measured temperatures, sample thickness, and exposure duration using a simple heat conduction relationship for thermally thick materials.

A procedure was developed to obtain effective thermal diffusivity of the sample "blankets" from the measured average steady-state temperatures at the front and back surfaces, thickness, and exposure time duration. This procedure, along with measurements in the heat penetration apparatus, can be used for routinely testing the various types and combinations of inorganic and organic fiber-based fabrics.

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1. Introduction

In the field, munitions (stored in wood crates and boxes and stacked on wood pallets) may be covered with blankets for fire and weather protection. The blankets, however, can be exposed to fire brands, hot ammunition fragments, and propellants during combat or in an accident. The U.S. Army estimates that under such a scenario, the blanket surface could be heated to temperatures as high as 2,000 to 3,000 °C for 6–10 s as a result of flame and heat penetration. Because of the high temperature exposure of the blanket surface due to flame and heat penetration, the stored munitions could possibly ignite, combust, and involve other munitions stored nearby, resulting in catastrophic fire and explosions. Thus, the U.S. Army is interested in using highly insulating and fire-resistant blankets to protect stored munitions in the field; the U.S. Army initiated a study in their own laboratory and at the Factory Mutual Research Corporation (FMRC), Norwood, MA, which is described in this report.

The objective of the study was to examine the resistance to flame and heat penetration of a combination of inorganic and organic fabrics. A literature search indicated that inorganic fiber-based fabrics have high fire resistance, and a combination of organic and inorganic fiber-based fabrics in layers are effective for fire protection. Contacts were made with several high-performance blanket manufacturers who are using technology developed by the National Aeronautical and Space Administration (NASA). Consequently, some of these manufacturers supplied the U.S. Army Research Laboratory (ARL) with a number of high-performance materials having thicknesses of 3–5 mm (defined as thin in this report) and 15–25 mm (defined as thick in this report). These high-performance fabric materials are identified as sample "blankets" in this report. Each sample's blanket resistance to flame and heat penetration was assessed by the following two tests:

(1) Flame Penetration Tests - an oxyacetylene torch flame was used in the tests. The top surface of the sample blanket was wrapped around or stapled to a wooden block and exposed to

the oxyacetylene flame. Measurements were made of the extent of flame penetration through the sample blanket onto the woodblock.

(2) Heat Penetration Tests - the front surface of the sample blanket on top of three layers of Kevlar fabric,* as a backing fabric, was exposed to a known external heat flux value. Measurements were made for surface temperatures at the front and back of the sample blanket and at the back of each layer of the Kevlar fabric.

2. Background

A literature search was performed on the extent of flame and heat penetration of single and multiple layers of various organic and inorganic fiber-based fabrics; about 150 relevant papers and reports were found. Many studies indicated that resistance to flame and heat penetration increased by using layers of fabrics made from fibers of inorganic and organic polymers [1–12].

An example of using a combination of inorganic fiber-based fabrics is the heat blocking system used by NASA for thermally protecting atmospheric entry and hypersonic cruise vehicles [5]. The front and the back surfaces of the heat blocking system consist of four layers of aluminoborosilicate (ABS) fabric, with a fifth inner layer of silica fabric and thread. The core consists of a combination of layers of the following materials:

- silica felt (98.5% SiO2),
- ABS (62 % Al_2O_3, 14% B_2O_3, and 24% SiO_2),
- silica-felted fiber mat (999% SiO_2),
- alumina mat (95% Al_2O_3, 5% SiO_2), and
- silica felt (98.5% SiO_2).

The thermal properties of the five layers, constituting the core, are listed in Table 1.

* The U.S. Army uses Kevlar fabric in ballistic blankets (multiple layers of Kevlar fabric were used).

Table 1. Thermal Properties of NASA's Thermal Protection System for Atmospheric Entry and Hypersonic Cruise Vehicles[a]

Layers	Material	Density (kg/m^3)	Heat Capacity (kJ/kg-K)	Thermal Conductivity (kW/m-K) x 10^5	Thermal Diffusivity (mm^2/s)[b]
1	Silica felt ($98.5\%\ SiO_2$)	96	0.349	1.58	0.47
2	ABS ($62\%\ Al_2O_3$, $24\%\ SiO_2$, $14\%\ B_2O_3$)	96	0.388	2.16	0.58
3	Silica felted fiber mat ($99.9\%\ SiO_2$)	136	0.258	1.87	0.53
4	Alumina mat ($95\%\ Al_2O_3$, $5\%\ SiO_2$)	96	0.336	1.80	0.56
5	Silica felt ($98\%\ SiO_2$)	96	0.349	1.58	0.47

[a]Taken from Kourtides et al. [5].
[b]Thermal diffusivity = thermal conductivity/density and heat capacity.

The data in Table 1 indicate that thermal diffusivity values for inorganic fiber-based fabrics are between 0.47 and 0.58 mm^2/s. A combination of alumina and silica-based fabrics are likely candidates for sample blankets since they have low thermal diffusivity values.

An example of using a combination of inorganic and organic fiber based fabrics is the system used for the space shuttle Columbia [7]. The system consisted of silicone-impregnated glass fiber batting, sewn in covers of reinforced polyimide film with alternate layers of perforated polyimide film and dacaron (polyethylene terephthalate, PET) net, and a polyimide film cover. This combination had also been considered for high-temperature filtration, flame-resistant upholstery for commercial passenger vehicles, and aircraft crew uniforms.

The combination of inorganic and organic fibers is also used to enhance resistance to fuselage burnthrough in aircraft fuel fires [13]. Fuselage burnthrough refers to the penetration of an external postcrash fuel fire into an aircraft cabin. The time to burnthrough is critical because in survivable aircraft accidents, heat and fire products released from the cabin materials, ignited

by burnthrough from an external fuel fire, may incapacitate passengers before they are able to escape.

There are typically three barriers that a fuel fire must penetrate to burnthrough to the cabin interior: the aluminum skin (30–60 s resistance depending on thickness), the thermal acoustical insulation, and the interior sidewall and floor panel combination. Thermal acoustical insulation, typically comprised of fiberglass batting encased in a polyvinylfluoride (PVF, Tedlar) moisture barrier, provides 60–120 s of protection, as long as it is not dislodged from the fuselage structure. Honeycomb sandwich panels used in the sidewall and floor areas of transport aircraft offer a substantial fire barrier.

The efficiency of preventing or delaying the burnthrough of modified fiberglass batting or replacement insulation materials has been examined in full-scale fire tests using a reusable fuselage test rig [13]. Using polyimide (Kapton) film (an organic polymer) in place of PVF (Tedlar) film improved the burnthrough resistance. A layer of Nextel (tightly woven ABS fabric), placed inside each of the insulation batts and encapsulated in the standard metallized PVF (Tedlar) film, prevented the burnthrough for nearly 7 min. Most of the Nextel remained in place, except for one area about 20 in × 20 in (0.51 m × 0.51 m), which was penetrated.

Additional inorganic and organic fibers as insulation materials tested in full-scale fire tests with a reusable fuselage test rig consisted of [13]:

- Curlon - a heat-treated, oxidized polyacrylonitrile fiber (OPF) (70% carbon, 20% nitrogen, and 10% oxygen). Curlon was extremely effective in resisting flame penetration for at least 5 min during several full-scale tests.

- Solimide AC-430 System - the system consisted of rigid polyimide foam with Quartzel, a vitreous silica wool barrier. This system, however, was less effective than the system with the Nextel-enhanced fiberglass system and the Curlon.

- AstroquartzII System - the system consisted of an AstroquartzII ceramic mat with a thin layer of Nextel ceramic fiber paper. This system resisted flame penetration for over 8 min.

The Federal Railroad Administration [7] has also successfully tested glass fiber, ceramic fiber, and mineral fiber blankets for thermally protecting aluminum railroad tank cars from torch and pool fires.

Using inorganic and organic fiber-based fabrics is now commercialized for a variety of applications [8–12]. Table 2 lists some commercially available fabrics that could be considered for the sample blankets.* The amount of organic fibers is very small compared to inorganic fibers. For example, Nextel 312 sewing threads are a combination of Nextel 312 ceramic fibers and rayon fibers (10% by weight) [11].

3. Experimental Setup, Procedures, and Samples

Based on the information discussed in the previous section, several combinations of inorganic and organic fiber-based fabrics were selected as sample blankets for the study. The samples were subjected to flame and heat penetration tests.

3.1 Flame Penetration Tests. The flame penetration tests were performed by the ARL at Aberdeen Proving Ground, MD, for rapid fabric screening. Variable exposure times were used in the tests to define the limitations of the fabrics to flame exposure. The flame exposure limitation of the fabrics was further explored by using propellants between the fabric layers and wooden block.

* The list is not a comprehensive list. It is only an example of commercially available fabrics to use as sample blankets for thermal protection. These fabrics do not provide protection against ammunition penetration.

Table 2. Commercially Available Fabrics for Sample Blankets

Fabrics and Exposure Temperature Limit[a]	Reference No.
(1) Zetex, T ≤ 1,100 °F (593 °C) (inorganic fibers); (2) Zetex Plus, T ≤ 2,000 °F (1093 °C) (inorganic fibers)	8
(1) Kao-Tex 2,000 cloth, T ≤ 2000 °F (inorganic fibers); (2) calcium magnesium silicate, T ≤ 1,832 °F; (3) Kaowool ceramic fiber, B Blanket, T ≤ 1,800 °F (inorganic fibers); (4) Cerawool, T ≤ 1,800 °F (inorganic fibers); (5) Kaowool blanket S, T ≤ 2,300 °F (inorganic fibers); (6) Cerachem blanket, T ≤ 2,600 °F (inorganic fibers)	9
(1) Duraback, T ≤ 1,800 °F (inorganic fibers); (2) Durablanket 2,600, T ≤ 2,600 °F (1,430 °C) (inorganic fibers)	10
(1) Nextel 312 Ceramic fibers, T ≤ 2,600 °F (1,430 °C) (aluminoborosilicate); (2) Nextel 440 Ceramic fibers, T ≤ 3000 °F (1,648 °C) (aluminoborosilicate)	11
RM Therma-Shield insulation materials: (1) SuperSpan welding cloth; (2) Fluorel coated ceramic cloth ≤ 2,000 °F; (3) Therma-Shield2400 (alumina silica fiber with binders) ≤ 2,400 °F	12

[a]Detailed chemical compositions of the fabrics are not available, as they are proprietary materials. Temperature specifications are from the manufacturer's brochures.

The sample blankets used in the flame penetration tests are listed in Table 3. In these tests, a sample surface mounted on a block of wood was exposed to an Airco oxyacetylene torch with a no. 144-2 cutting tip. In some tests, propellants (fuel-oxidizer mixture used for launching rockets) were placed between the sample and wood surface. The oxygen and acetylene gas pressures on the torch were set at 40 psi (276 kPa) and 5 psi (34 kPa), respectively. The tip of the flame was kept between 13 and 25 mm (0.5 to 1 in) above the center of the sample surface. Some samples ignited as soon as the oxyacetylene flame was brought close to the surface. In these test samples, the torch was removed as soon as the sample was ignited, but it was allowed to burn for about 10 s more. In the absence of ignition, the exposure time was extended up to a maximum exposure time of 80 s. Flame penetration depths and visual observations were made while testing the samples. Three sets of tests were performed, where sample dimensions, the thickness of the wooden block, and the modes of attachment were varied. The three tests are described as follows.

First Set of Tests (thick wooden block, metal frame). In these tests, 152-mm (6-in) square-samples were used. The samples were mounted on top of 152-mm (6-in) square and 51-mm (2-in) thick blocks of dry pinewood. A 152-mm (6-in) square, 25-mm (1-in) wide, and 3-mm (0.12-in) thick metal frame with a 102-mm (4-in) square opening was used on top of the sample surface to keep it stable during the test. The sample surface was exposed to the flame for various times (3–80 s) to define the limitations of the fabrics to flame exposure. Samples A through I in Table 3 and their combinations were used in the tests.

Second Set of Tests (thin wooden block, metal frame). In these tests, the same metal frame from the first set of tests was used on top of the fabric surface. The fabric samples were mounted on top of 190-mm (7.5-in) square and 19-mm (0.75-in) thick blocks of dry pinewood. The sample surface was exposed to the flame for various times (6–10 s) to define the limitations of the fabrics to flame exposure. Samples J through O in Table 3 and their combinations were used in the tests.

Third Set of Tests (larger sample area, thin wooden block, no metal frame). In these tests, 254-mm (10-in) square and 152-mm × 356-mm (6 × 14 in) rectangular samples were used. The samples were stapled on top of 190-mm (7.5-in) square and 19-mm (0.75-in) thick and 140-mm × 152-mm (5.5 × 6.0-in) and 38-mm (1.5-in) thick blocks of dry pinewood, respectively. The sample surface was exposed to the flame for 6–10 s. Samples J, P, Q, and R in Table 3 were used.

3.2 Heat Penetration Tests. The heat penetration tests were performed by the Factory Mutual Research Corporation in Norwood, MA, in the heat penetration apparatus shown in Figure 1. Sample blankets consisting of combinations of mostly alumina, silica, and ceramic based fabrics (inorganic fabrics), with a backing made of three layers of Kevlar fabric (organic fabric), were used. Sample blankets were selected based on the test data from the flame penetration tests and background information from the literature.

Table 3. Sample Blankets for Flame Penetration Tests

Sample	Name[a]	Description[a]
A	Silica Cloth 399C-1	94% silica; service temperature up to 2,000 °F (continuous heating) and 3,000 °F (short-term heating); weight: 18 oz/yd^2; thickness: 0.030 in; Cotronics Corp, Brooklyn, NY.
B	Felt Insulation 370-1	Silica fibers; service temperature up to 2,300–3,000 °F; density: 12 lb/ft^3 for a thickness: 0.13 in and 8 lb/ft^3 for a thickness of 0.25 in; Cotronics Corp, Brooklyn, NY.
C	HTX-1000-9N	94% silica similar to A but thicker - a woven continuous filament amorphous silica fabric with a proprietary coating; service temperature: up to 1,800 °F; weight: 33 oz/yd^2; thickness: 0.046 in; Amatex Corporation, Morristown, PA.
D	Nextile 312 (AF 40)	Woven from continuous aluminborosilicate fibers; service temperature up to 2,200 °F (continuous) and 2,600 °F (short term); weight: 25.0 oz./yd^2; thickness: 0.039 in.; melting point: 3,272 °F; 3M Company, St. Paul, MN.
E	Siltemp25M Mat	96% silica high temperature insulation made from amorphous silica; service temperature: up to 2,000 °F; density: 13 lb/ft^3; nominal thickness of 0.23 in; Ametek, Wilmington, DE.
F	Kevlar/fiber glass 22PT30	Medium weight Aramid fiber blends over a fiberglass yarn; service temperature up to 650 °F; weight 22 oz/yd^2; thickness: 0.060 in; Amatex Corporation, Morristown, PA.
G	Nomex III Aramid blend	Weight: 7.5oz/yd^2; Southern Mills, Union City, GA.
H	Fiberglass	Woven ceramic fibers; weight: 24 oz/yd^2; thickness: 0.025 in; JPS Glass Company, Slater, SC.
I	Silicone coated silica cloth HT 1000-9N-SRI	94% silica woven continuous filament amorphous silica fabric with silicone rubber coating on one side; service temperature up to 1,800 °F; weight: 42 oz/yd^2; thickness: 0.054 in; Amatex Corporation, Morristown, PA.
J	Norfab Kevlar-glass style 30PT20DC; 30 oz/yd^2.	
K	3M Nextile fabric style 440.	
L	Ceramic fabric style 399C-2.	
M	Ceramic fiber batting 370-1; 1/8 in.	
N	Ceramic fiber batting 370-4; 1/2 in.	
O	Ballistic blanket - 13 layers of Kevlar fabric.	
P	Kevlar-nomex fabric style 5450; 9.2 oz/yd^2.	
Q	Amatex mineral coated glass style G26T33-7B; 9.2 oz/yd^2.	
R	Carbon fiber batting; 7 oz/yd^2.	

[a] Names and information are from the manufacturers' brochures; the units are same as reported in the brochures.

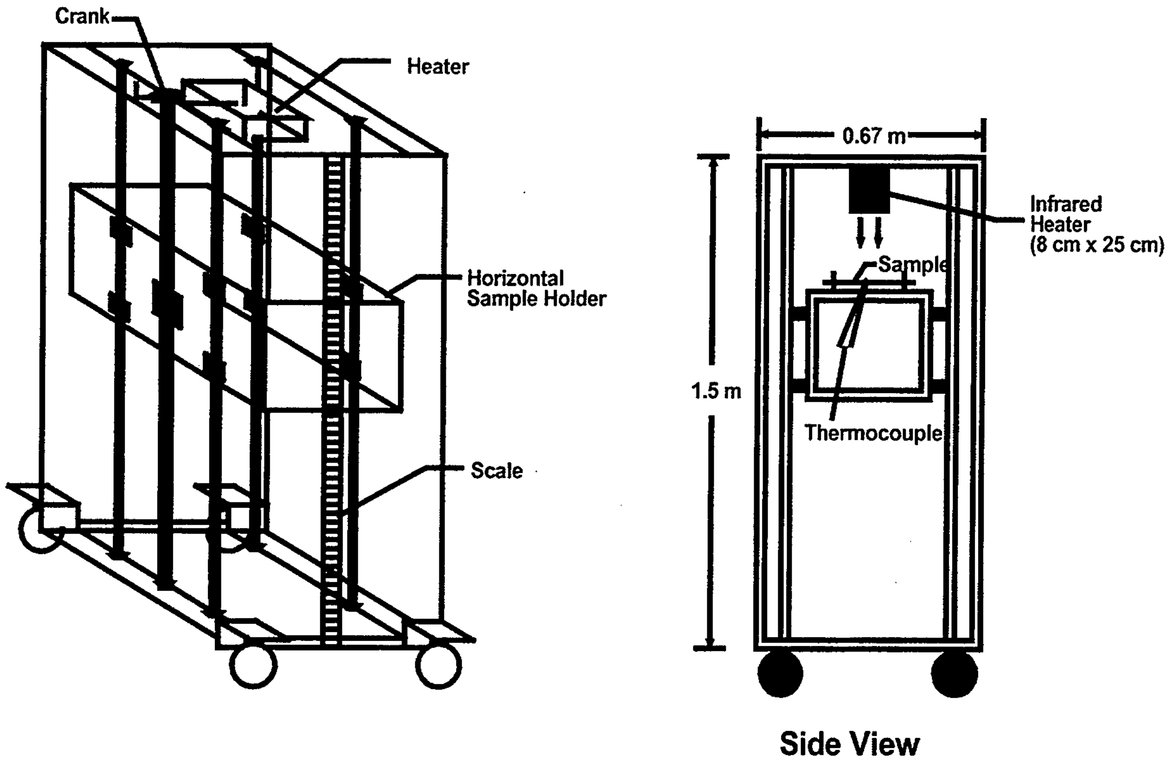

Figure 1. Heat Penetration Apparatus.

The heat penetration apparatus consisted of a single infrared heater* (Model 5208-10, Research Inc., Minneapolis, MN) attached at the top of a 1.5-m (5-ft) high, 0.67-m (2-ft) long, and 0.67-m (2-ft) wide metal frame with wheels. The heater had a cross-section of 80 mm × 250 mm (3 in × 10 in). A controller (Model 5620, Research Inc., Minneapolis, MN) was used to adjust the output of the radiant heater.

A 100-mm-square and 19-mm-thick horizontal "DuPont proprietary" polymer block was used as the sample holder. The polymer block acted as an insulator, retaining most of the heat

* The emitter is a tungsten filament (in an argon atmosphere) enclosed in a 9.5-mm outer diameter clear quartz tube. The emitter operates at approximately 2,205 °C at rated voltage and 2,983 °C at twice rated voltage, with a 1.15-μm and 0.89-μm spectral energy peak, respectively.

that penetrated through the sample blanket. The platform was moved in a vertical direction to change the external heat flux value at the sample surface. A Medtherm heat flux gauge was used to calibrate the heat flux from the radiant heater to the sample surface. The calibration is shown in Figure 2. The heat flux increases with decreasing distance between the sample surface and the radiant heater, and it reaches a maximum of about 200 kW/m^2, for a distance of 30 mm between the sample surface and the heater.

In each test, the sample blanket, with three layers of Kevlar fabric at the back, was placed on top of the horizontal polymer block sample holder, as shown in Figure 3. Because the polymer block acted as an insulator and retained most of the heat penetrating through the sample blanket, the temperature of the three layers of Kevlar fabric continued to increase, even after the exposure to the front surface of the sample blanket was terminated.

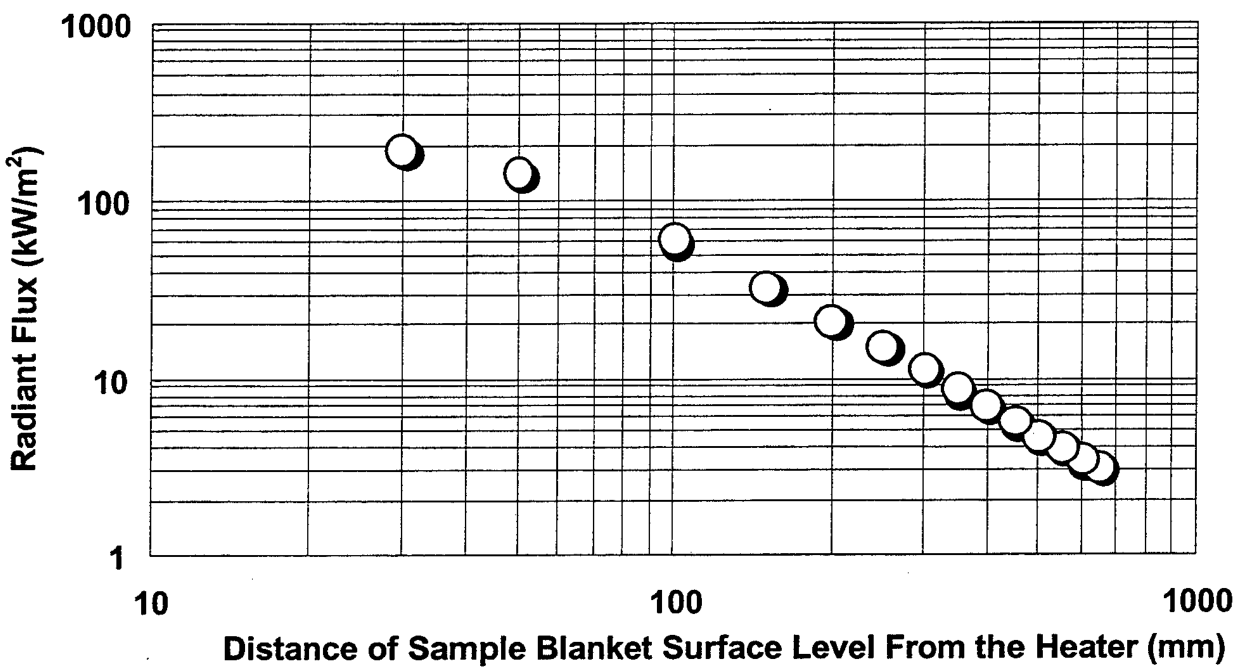

Figure 2. Measured Radiant Heat Flux at the Sample Surface vs. Distance Between the Surface and the Radiant Heater in the Heat Penetration Apparatus.

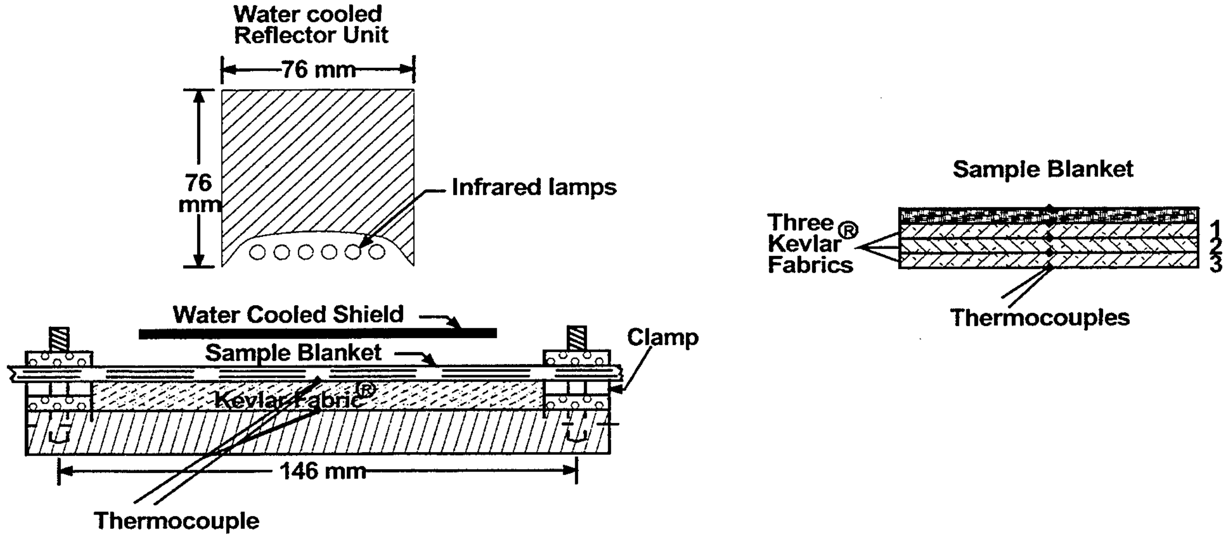

Figure 3. Arrangement of the Sample Blanket With Three Layers of Kevlar Fabric at the Back of the Sample Blanket on the Horizontal Platform of the Heat Penetration Apparatus.

Five thermocouples at each layer were used to measure the front and back surface temperatures (T_s and T_u, respectively) of the sample blanket, and the back surface temperatures of each layer of the Kevlar fabric (T_{k1}, T_{k2}, and T_{k3}). A water-cooled shield was used to block the heat exposure of the sample blanket until the radiant emission from the heater was stabilized (20 s).

For the temperature measurements, K-type chromel-alumel thermocouples (Omega) were used. The thermocouples were attached to the fabric surfaces with high temperature adhesive. The thermocouples were connected to a data processor (Analog Device, Signal Processor Model 5B47-K-04). The data processor was connected to a data logger (DL1, Prototype Unit) interfacing with a Gateway 2000 PC with a Windows 95 operating system through its serial communication port. A software package LITEUP was used to instruct the hardware to read the data. The software package LITESHOW was used to stop the data acquisition and offload the data into a data file. The software package XLITE was used to convert the data file to a text file. The test was started by placing the sample blanket on the horizontal platform, turning on the data processor, data logger, and the Gateway 2000 PC, and initiating the software package LITEUP

with the name of the data file. The heater was then turned on with the water-cooled shield in place to block the heat exposure of the sample blanket. The heater was allowed to stabilize for 20 s, at which time the water-cooled shield was moved away, exposing the sample blanket surface to the preset heat flux value. In each test, the sample blanket was exposed to heat flux for a fixed exposure time (10–120 s). The temperature was measured every 0.05 s at five locations (at the front and back surfaces of the sample blanket and at the back surfaces of the three layers of Kevlar fabric).

At the end of the exposure, the heater was turned off. The software application LITESHOW cancelled the data acquisition and offloaded the data into a data file. The thermocouple data imported as voltages was converted to °C and recorded into the Microsoft Excel temperature worksheet as one a 1 s running average (the temperature was recorded every 0.05 s and thus an average of 20 data points).

The sample blankets tested in the heat penetration apparatus are listed in Table 4. The samples consist of layers of alumina, silica, and calcium-oxide-based fabrics (inorganic polymer fibers based fabrics). These fabrics were similar to those listed in Tables 1 and 2. Combinations of numbers 1,000, 800, and 600 designate various types of fiberglass materials, and CH represents silica fiber. Nextel consists of woven aluminoborosilicate fibers.

Four sample blankets were thin (3–5 mm) and five sample blankets were thick (15–25 mm). The manufacturers did not provide detailed chemical compositions of the samples, as they were assembled from the proprietary nature and combinations of fabrics.

3.3 Setting Exposure Conditions. The goal of the sample blanket exposure tests was to expose the surface to a high enough temperature for longer times, without ignition, and to use the data for extrapolation to higher temperatures (possibly up to 3,000 °C) and exposures up to 60 s.

Several exploratory tests were performed to set the exposure conditions without igniting the sample. For the exploratory tests, two thin sample blankets (nos. 1, 3, and 4) and a thick sample

Table 4. Sample Blankets for Heat Penetration Tests

Sample	Fabric Arrangement	Fabrics Layers[a]	Thickness/Side Exposed
Thin Sample Blankets			
No. 1	Shiny Shiny	1,000/600 aluminum; AF – 62 Nextel 1,000/600 aluminum	3 mm thick
No. 2	Beige Black	188 CH; 0.13-in Kaowool paper Rubberized silica	5-mm-thick beige
No. 3	Light green Gray	Zetex 10615-1860; 0.13-in Kaowool paper; 84 GHS	5-mm-thick Zetex
No. 4	Creamy Creamy	Ceramic fabric 399C-2 0.13-in Ceramic blanket Ceramic fabric 399C-2	5 mm thick
Thick Sample Blankets			
No. 5	Shiny Beige	1,000/600 aluminum - Copper knit 500; 188 CH	15-mm-thick beige
No. 6	Silver silica Beige	1,000/500 stainless steel foil 0.5-in Kaomat; 188 CH	20-mm-thick beige
No. 7	Orange silicone Beige	1,000/500 OS; 0.5-in 607 Superwool; 188 CH	20-mm-thick beige
No. 8	Shiny Beige	1,000/800 aluminum; 0.5-in Kaowool – S; 188 CH	20-mm-thick beige
No. 9	Fiberglass eave Shiny	1000/800 stainless steel foil; 0.5-in 607 Superwool; 1,000/600 aluminum	25-mm-thick fiberglass

[a] Sample details are from the manufacturers' catalogue.

blanket (no. 8) were used. The tests were performed with an unpainted surface and black painted* surface. The sample surface was exposed to 20, 50, and 84 kW/m^2 for short (10–20 s), intermediate (100 s), and longer (120 s) exposure, where the sample was not ignited. Unpainted surfaces of samples no. 1 and no. 4 were used for short and intermediate exposures (10, 20, and 100 s, Table 5), whereas painted and unpainted surfaces of samples of nos. 3, 4, and 8 were used for longer exposure of 120 s.

*A solar-collector flat black paint was used.

Table 5. Exploratory Tests With Short Exposure Duration of the Unpainted Sample Surface

Test No.	Sample Blanket No.	Heat Flux (kW/m^2)
1	1	20
2	1	20
3	1	50
4	4	20
5	4	50
6	4	50
7	4	84

Short and intermediate exposures were used to possibly avoid igniting the sample blanket. However, the short and intermediate exposures of 10, 20, and 100 s were found to be unsatisfactory, as the temperature rise at the front surface of the sample blanket was quite low, and the back surface temperature was close to ambient.

The second set of exploratory tests used unpainted and black painted surfaces of samples nos. 3, 4, and 8. The surfaces were exposed to 84 kW/m^2 for 120 s. The test data are shown in Figures 4–6.

The surface temperature for the black painted surface is higher, and the steady state is longer without the ignition of the sample. Data for the unpainted surface is unsatisfactory because of the low surface absorptivity. For example, the temperature profile for sample no. 8 in Figure 4 indicates that the surface temperature of the beige side (188CH) is about 1.5 × the temperature of the shiny side (1,000/800 aluminum, Figure 4). Thus, a black painted surface exposed at 84 kW/m^2 for 120 s was selected for heat penetration testing.

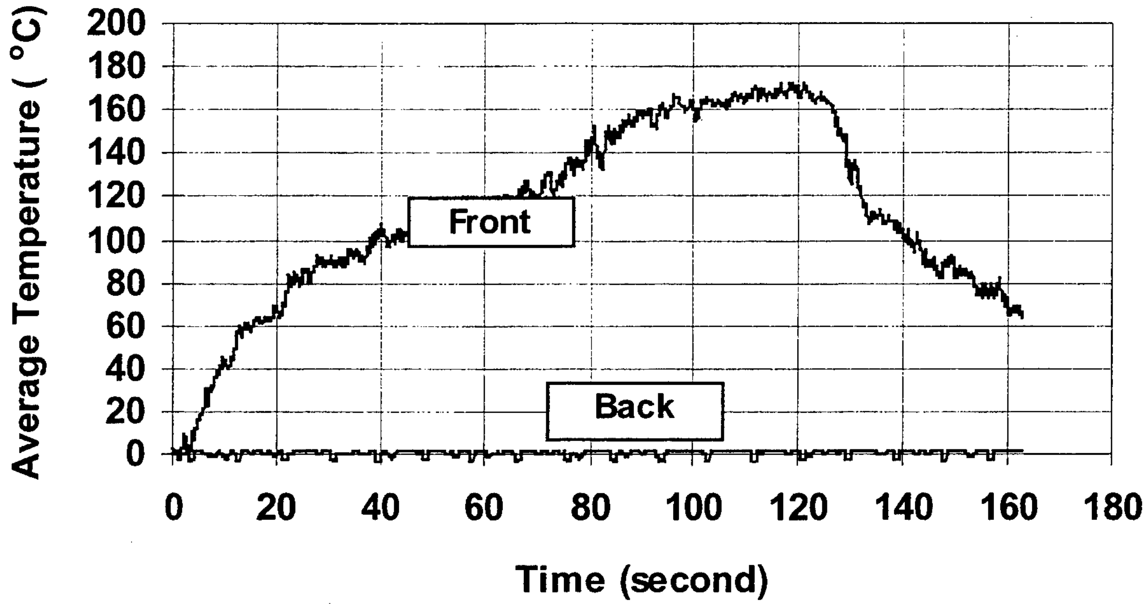

Figure 4a. Average Front and Back Surface Temperatures Above Ambient of 20-mm-Thick Sample Blanket No. 8. Unpainted Shiny Surface (1,000/800 Al) Was Exposed to 84 kW/m^2 for 120 s.

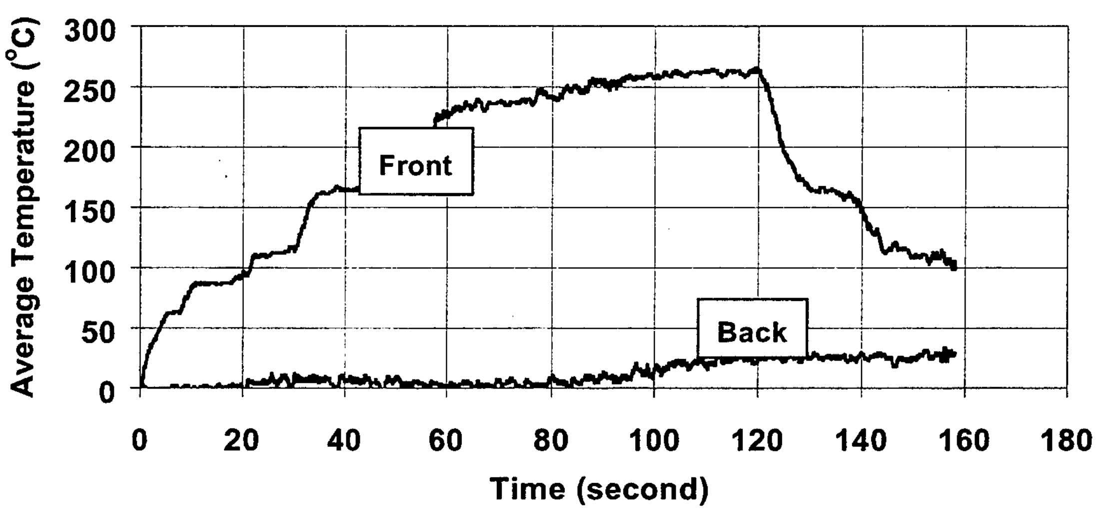

Figure 4b. Average Front and Back Surface Temperatures Above Ambient of 20-mm-Thick Sample Blanket No. 8. Unpainted Beige Surface (188 CH) Was Exposed to 84 kW/m^2 for 120 s.

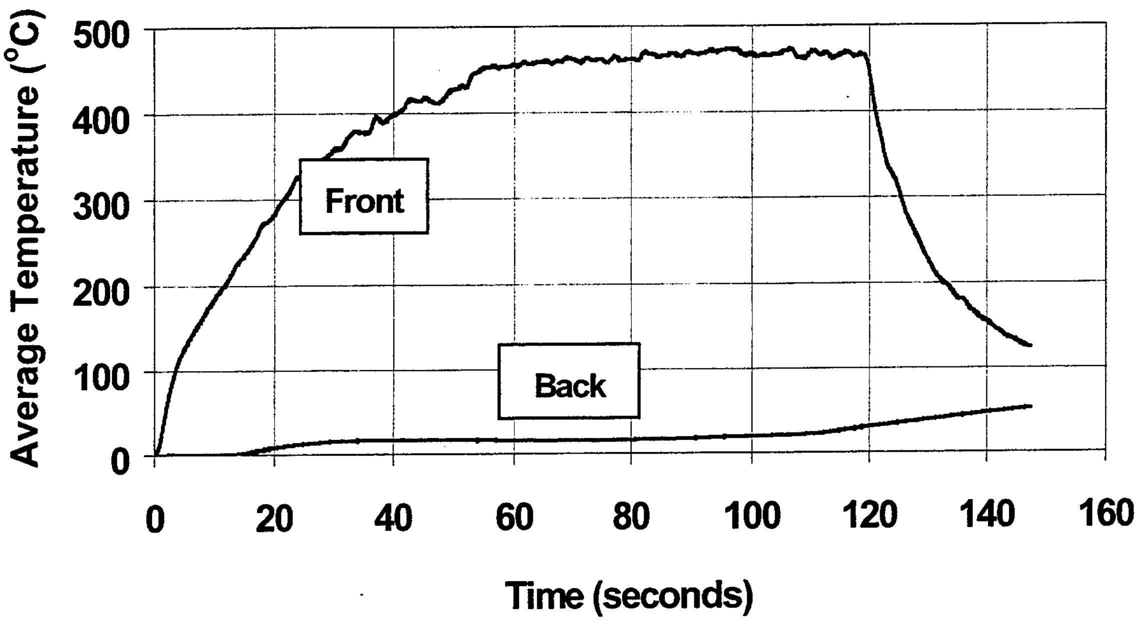

Figure 4c. Average Front and Back Surface Temperatures Above Ambient of 20-mm-Thick Sample Blanket No. 8. Black Painted Beige Surface (188 CH) Was Exposed to 84 kW/m^2 for 120 s.

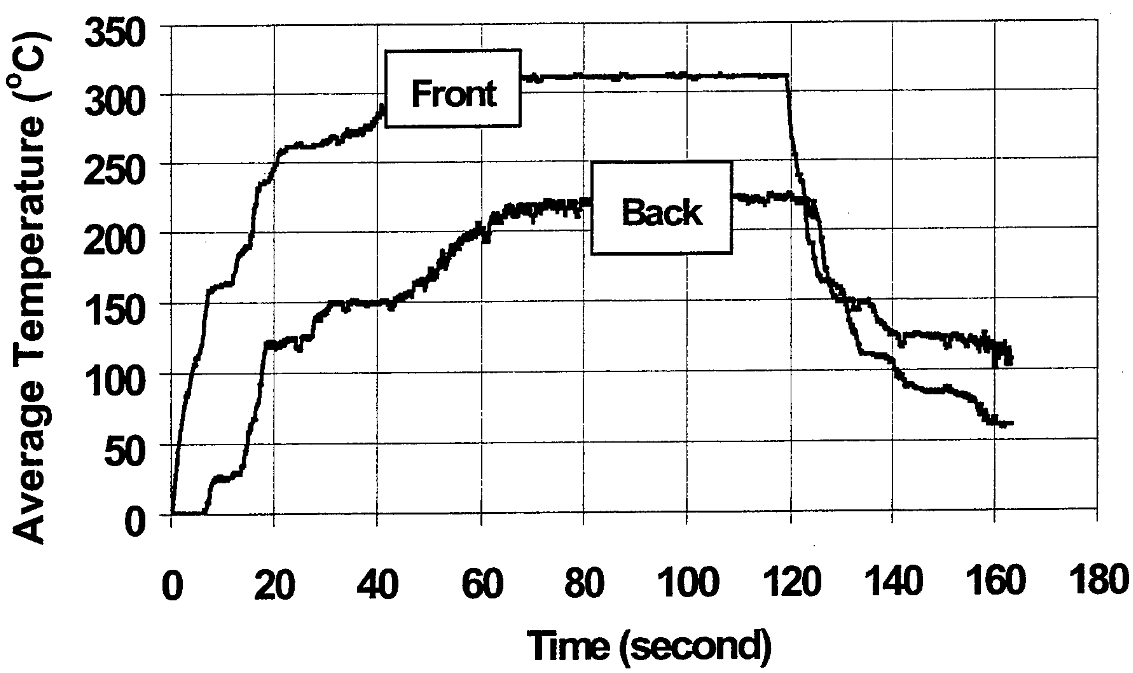

Figure 5a. Average Front and Back Surface Temperatures Above Ambient of 5-mm-Thick Sample Blanket No. 3. Unpainted Surface Was Exposed to 84 kW/m^2 for 120 s.

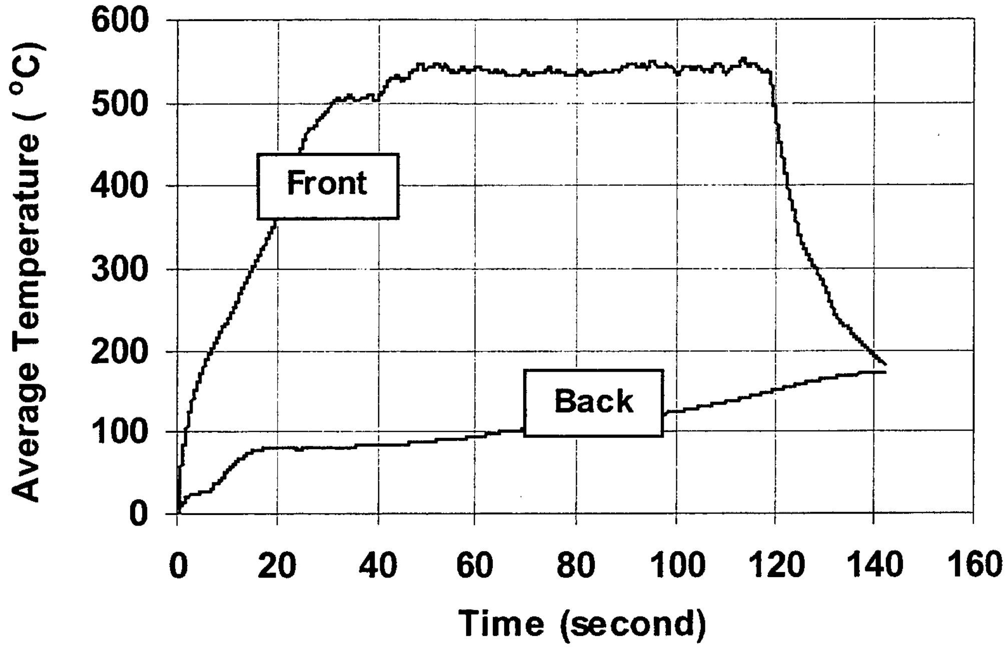

Figure 5b. Average Front and Back Surface Temperatures Above Ambient of 5-mm-Thick Sample Blanket No. 3. Black Painted Surface Was Exposed to 84 kW/m^2 for 120 s.

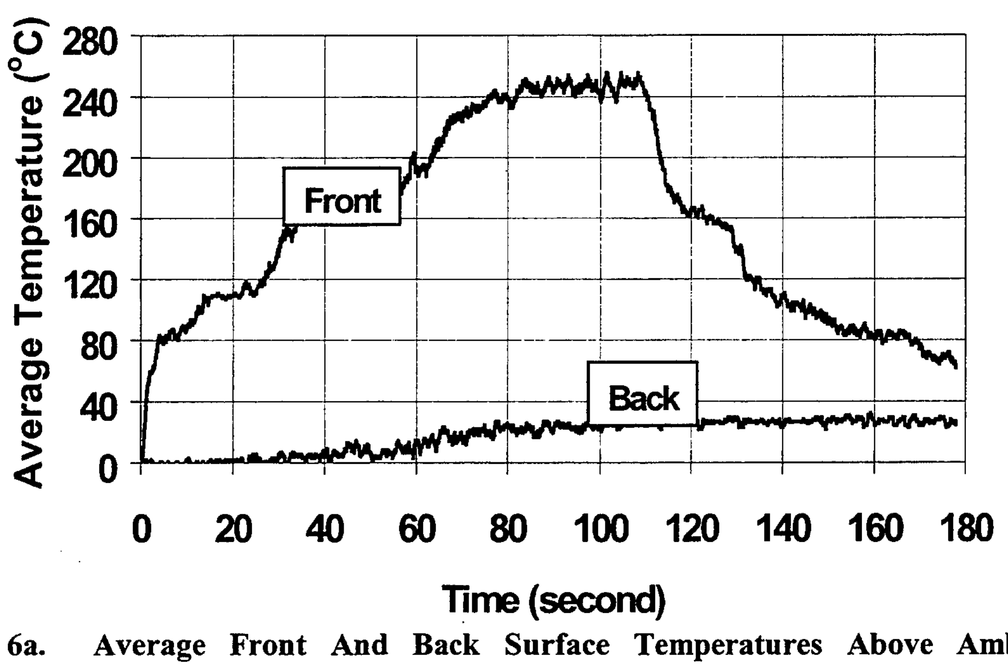

Figure 6a. Average Front And Back Surface Temperatures Above Ambient of 5-mm-Thick Sample Blanket No. 4. Unpainted Surface Was Exposed to 84 kW/m^2 for 120 s.

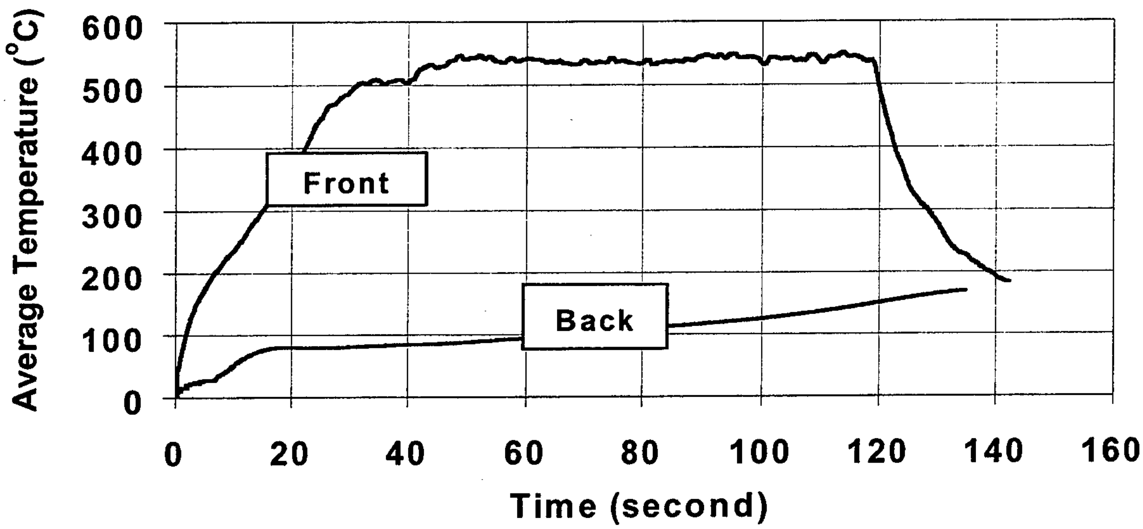

Figure 6b. Average Front and Back Surface Temperatures Above Ambient of 5-mm-Thick Sample Blanket No. 4. Black Painted Surface Was Exposed to 84 kW/m^2 for 120 s.

4. Experimental Results of Flame Penetration Tests

Resistance to flame and heat penetration for sample blankets made of layers of inorganic fiber-based fabrics was examined in the study. Resistance to flame penetration was examined in the flame penetration tests, and resistance to heat penetration was examined in the heat penetration tests.

In the flame penetration tests, samples were held on top of a 19 to 51-mm-thick dry pinewood block by a metal frame or by staples. The sample surface was exposed to an oxyacetylene flame for various time durations to define the limitations of the fabrics to flame penetration. The flame penetration limitation of the fabrics was further explored by using propellants between the fabric layers and wooden block. The samples used in the tests are listed in Table 3.

4.1 Test Results From the First Set of Tests. In the tests, samples were mounted on 51-mm-thick dry pinewood blocks with a metal frame. The sample surface was exposed to an oxyacetylene flame for 3–80 s. The test results are listed in Table 6.

The data in Table 6 show that a combination of silica-based samples is more effective in resisting flame penetration. In terms of avoiding charring the wood surface, the following silica-based sample combinations appear to be effective.

- A silica cloth (#A)/felt insulation (#B-silica fibers)/silica cloth (#A) combination.
- An HTX/1000-9N (#C, silica similar to #A)/Siltemp (#E-silica insulation) combination.
- A silicone coated silica cloth (#I)/Siltemp (#E-silica insulation) combination.

4.2 Test Results From the Second Set of Tests. In the tests, samples were mounted on 19-mm-thick dry pinewood blocks with a metal frame. The sample surface was exposed to an oxyacetylene flame for 10 s. The test results are listed in Table 7. Observations in Table 7 show that ceramic-based samples are able to resist flame penetration. The sample combinations which are effective in preventing flame penetration (no hole) are (a) ceramic fabric (#L) over ceramic fiber batting (#M and #N) and (b) ceramic fabric (#L) with ceramic fiber batting (#M) over a Kevlar ballistic blanket (#O).

4.3 Test Results From the Third Set of Tests. In the tests, large, mostly organic fiber-based fabric samples were stapled onto 19- and 38-mm-thick dry pinewood blocks. The sample surface was exposed to an oxyacetylene flame for 10 s. The test results are listed in Table 8. The information in the table shows that none of the organic fiber-based fabrics as single or multiple layers prevented the flame from penetrating into wooden block. Thus, it is necessary to use a combination of inorganic and organic fabrics in multiple layers.

Table 6. Flame Penetration Into Dry Pinewood Block With Smaller Samples

Test No.	Sample Blanket on Wooden Block Surface	Exposure Duration (s)	Fabric/Wood Behavior
1	No sample, wood surface exposed.	3	wood charred
2	SiO_2 cloth (#A).	6	wood charred
3	Silica cloth (#A) heated to 767 °C.	20	pyrolysis of wood
4	Silica cloth (#A) over black powdered propellant on wood surface. Propellant exploded in 11 s.	11	wood and fabric charred
5	1/8-in Silica felt (#B).	10	wood charred
6	#A/#B layer heated to 700 °C.	60	charring; no flaming
7	#A/#B/#A layer heated to 750 °C.	80	third layer slightly browned; wood slightly charred
8	Nextile (#D).	6	burnthrough; charred wood
9	#D/#D.	6	less severe burnthrough than test 8
10	Siltemp (#E)	40	fabric bottom charred
11	Kevlar/fiber glass (#F) heated to 775 °C.	5	wood burned
12	Kevlar/fiber glass (#F) heated to 700 °C.	4	fabric burnthrough
13	Nomex III Aramid (#G).	3	fabric burnthrough
14	HTX1000-9N silica (#C) heated to 800 °C.	15	wood burned
15	#C/#E.	54	wood did not char
16	Woven ceramic fibers/Fiberglas (#H).	7	burnthrough
17	Silicone coated silica cloth (#I).	10	slightly charred
18	#I/#E.	30	no char
19	#C/#E + propellant on top of blanket.	propellant ignited	no char
20	#C/#E + propellant between the sample and wooden block.	propellant ignited immediately	wood and bottom blanket charred
21	#I/#E + propellant on top of blanket.	propellant ignited immediately	no char
22	#I/#E + propellant between the sample and wooden block.	propellant ignited immediately	wood and bottom blanket charred

Table 7. Flame Penetration Into Dry Pinewood Block With Smaller Samples for 10 s Exposure

Test	Sample Combinations	Measured Wood Char Depth (mm)	Observations
23	Kevlar-glass (#J) over ceramic fiber batting (#N)	13	64-mm square hole on the sample surface
24	Ceramic fiber batting (#N)	9	51-mm × 64-mm hole on the sample surface
25	Nextile fabric (#K) over ceramic fiber batting (#M)	6	51-mm × 64-mm hole on the sample surface
26	Nextile fabric (#K) over ceramic fiber batting (#N)	5	51-mm × 64-mm hole on the sample surface
27	Ceramic fabric (#L)	5	25-mm × 19-mm hole on the sample surface
28	Ceramic fabric (#L) over ceramic fiber batting (#M)	none	no hole
29	Ceramic fabric (#L) over ceramic fiber batting (#N)	none	no hole
30	Kevlar ballistic blanket (#O)	3	13-mm × 15-mm hole on the sample surface; 76-mm × 89-mm wood burned
31	Kevlar ballistic blanket (#O) over ceramic fabric (#L)	none	2-mm penetration into sample
32	Ceramic fabric (#L) with ceramic fiber batting (#M) over Kevlar ballistic blanket (#O)	none	no penetration into sample

5. Experimental Results of Heat Penetration Tests

In the tests, a single layer of each sample blanket (Table 4) on top of three layers of Kevlar fabric were exposed to an external heat flux of 84 kW/m^2 for 120 s. Temperature vs. time measurements were made at the front and back surfaces of the sample and at the back surfaces of the three layers of the Kevlar fabric.

Table 8. Flame Penetration Into Dry Pinewood Block With Larger Samples for 10 s Exposure

Test	Sample Combinations	Measured Wood Char Depth (mm)	Observations
33	Kevlar-nomex fabric (# P) on 38-mm-thick wooden block	10	sample burned off
33	Kevlar-glass (#J) on 38-mm-thick wooden block	13	25-mm × 64-mm hole on the sample surface
34	Amatex mineral coated glass (#Q) on 38-mm-thick wooden block	10	64-mm × 76-mm hole on the sample surface
35	Two layers of Kevlar-glass (#J) on 19-mm-thick wooden block	9	13-mm × 19-mm hole on the sample surface
36	Two layers of (Kevlar-glass (#J) + carbon fiber batting (#R)) on 19-mm-thick wooden block	14	13-mm × 25-mm hole on the sample surface
37	Two layers of (Kevlar-glass (#J) + two layers of carbon fiber batting (#R) on 19-mm-thick wooden block	14	10-mm × 19-mm hole on the sample surface

5.1 Front and Back Temperatures of the Sample. The measured data for the front and back temperatures of the sample are shown in Figures 4c (no. 8), 5b (no. 3), and 6b (no. 4), and in Figures 7–12. An examination of the front and back surface temperature profiles in the figures indicates that the delay in the rise of back surface temperature depends on the sample thickness and make up. For thin samples (thickness: 3–5-mm, nos. 1–4), the rise in the back surface temperature was started between about 20 and 60 s. For thicker samples (thickness: 20–25 mm, nos. 6–9), the rise in the back surface temperature started between about 80 and 130 s. For sample no. 5 (15 mm thick), there was negligible increase in the back surface temperature.

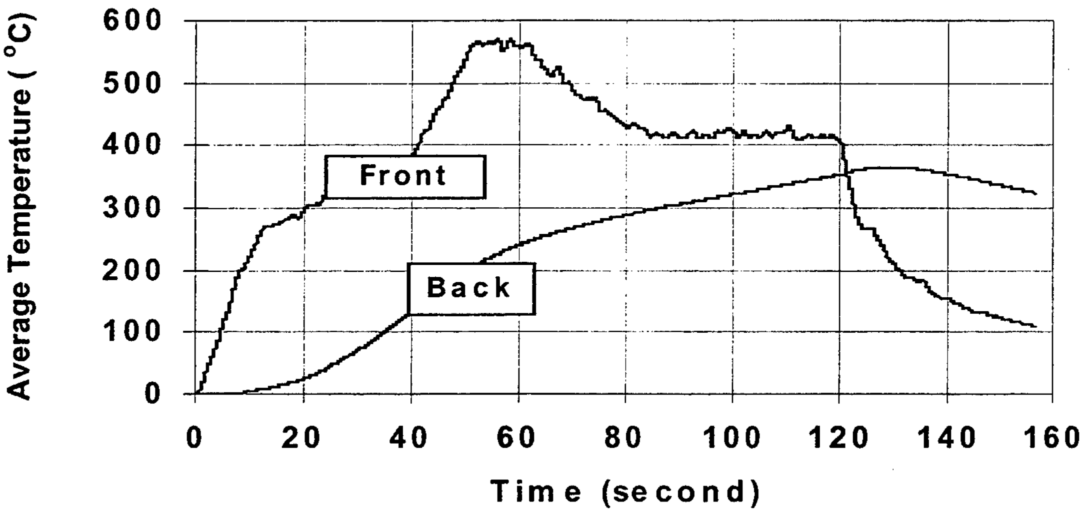

Figure 7. Average Front and Back Surface Temperatures Above Ambient of 3-mm-Thick Sample Blanket No. 1. Black Painted Surface Was Exposed to 84 kW/m^2 for 120 s.

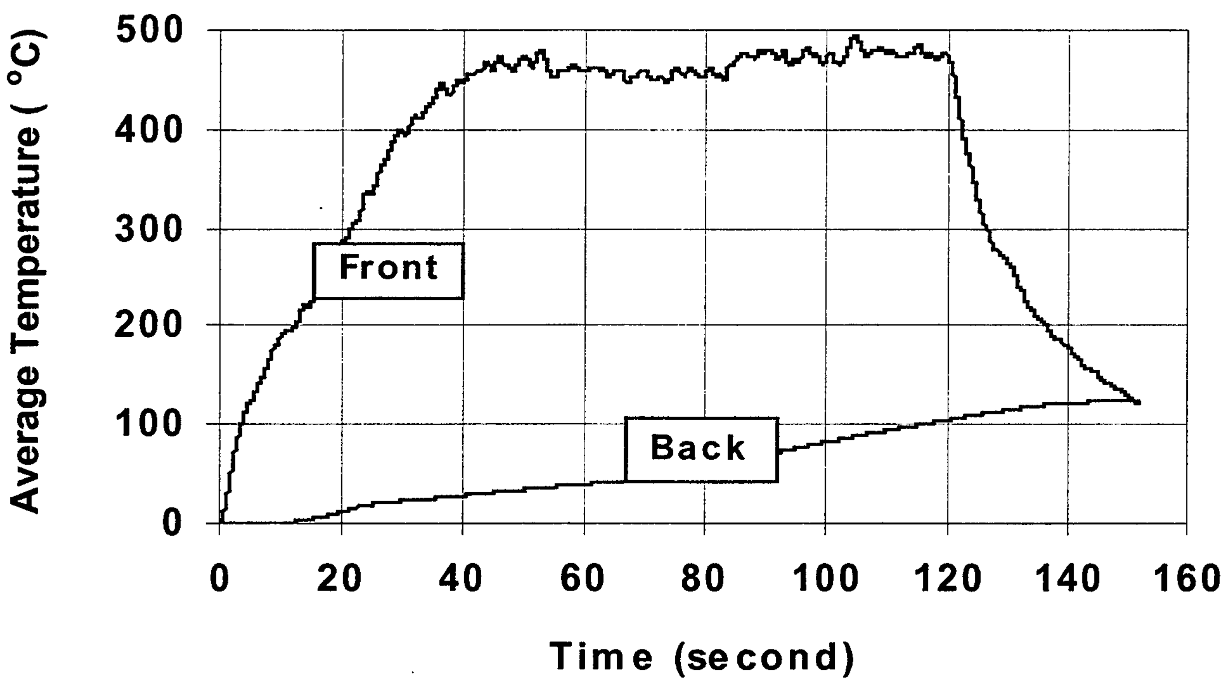

Figure 8. Average Front and Back Surface Temperatures Above Ambient of 5-mm-Thick Sample Blanket No. 2. Black Painted Surface Was Exposed to 84 kW/m^2 for 120 s.

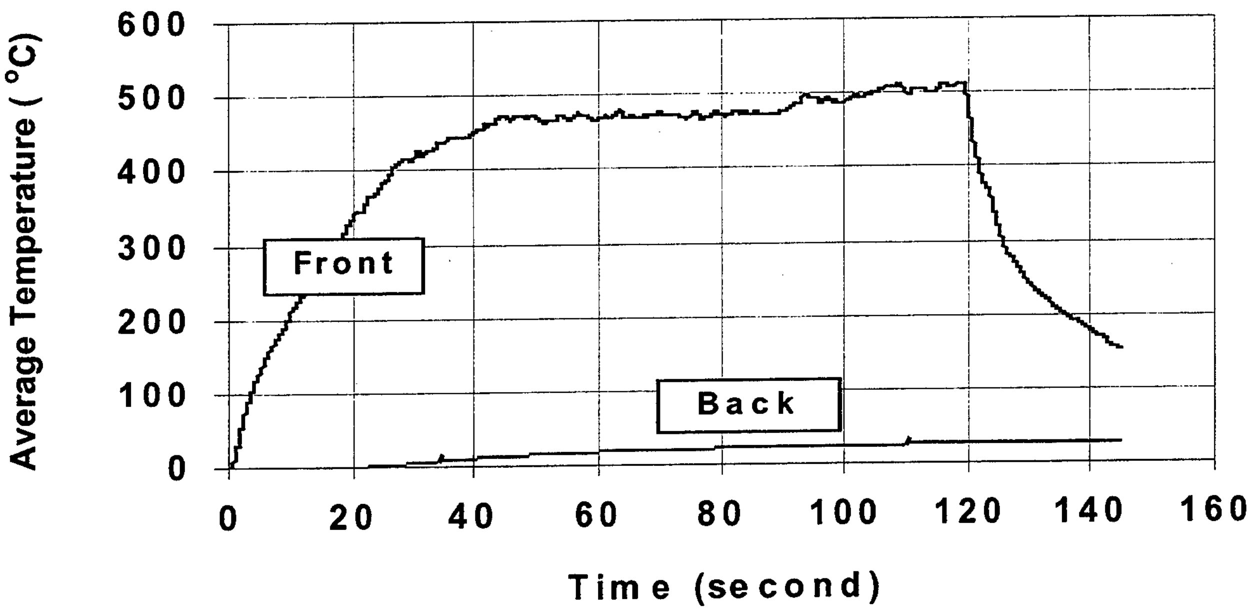

Figure 9. Average Front and Back Surface Temperatures Above Ambient of 15-mm-Thick Sample Blanket No. 5. Black Painted Surface Was Exposed to 84 kW/m^2 for 120 s.

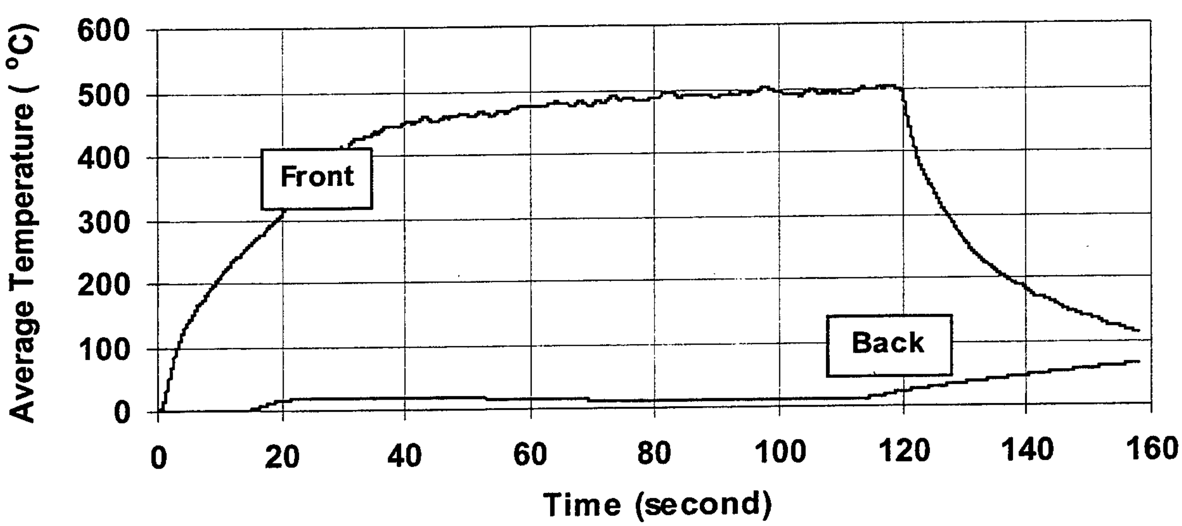

Figure 10. Average Front and Back Surface Temperatures Above Ambient of 20-mm-Thick Sample Blanket No. 6. Black Painted Surface Was Exposed to 84 kW/m^2 for 120 s.

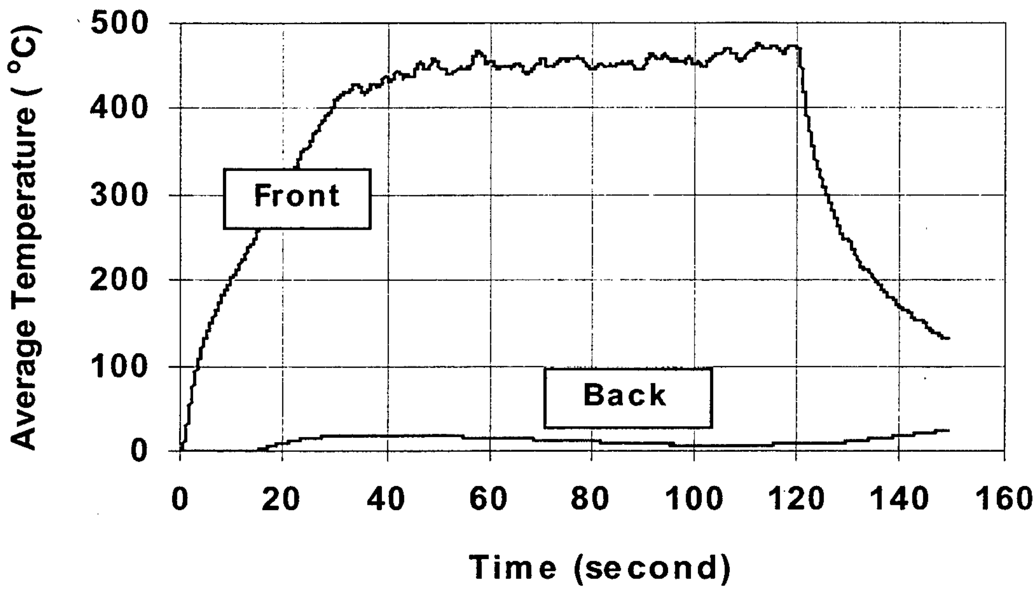

Figure 11. Average Front and Back Surface Temperatures Above Ambient of 20-mm-Thick Sample Blanket No. 7. Black Painted Surface Was Exposed to 84 kW/m^2 for 120 s.

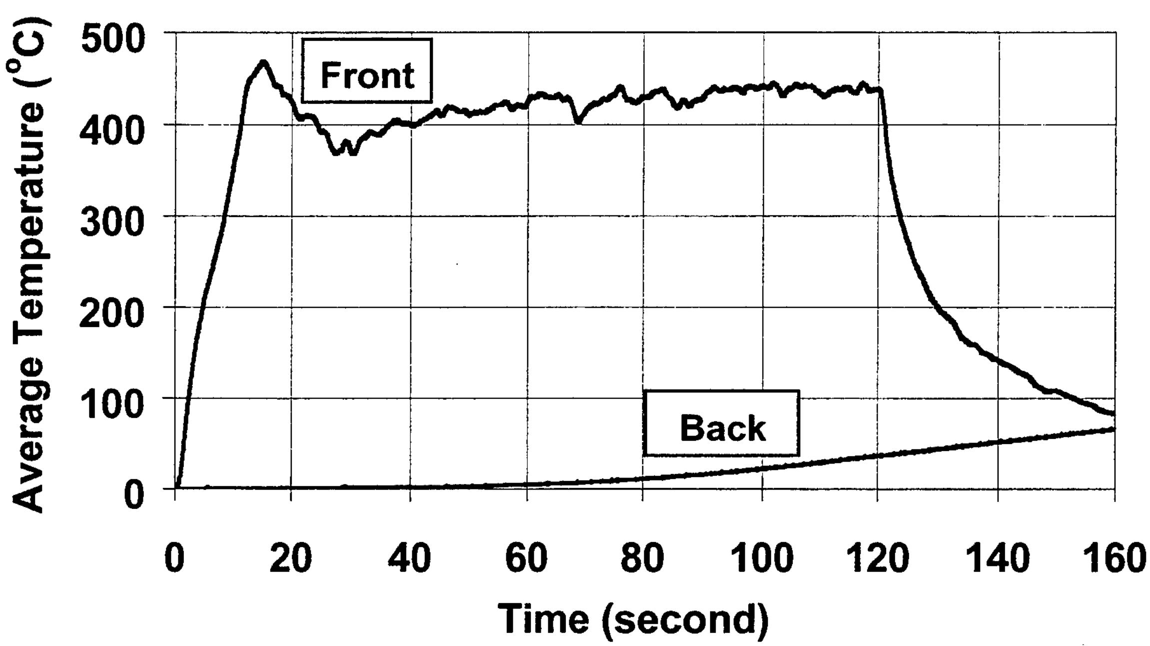

Figure 12. Average Front and Back Surface Temperatures Above Ambient of 25-mm-Thick Sample Blanket No. 9. Black Painted Surface Was Exposed to 84 kW/m^2 for 120 s.

5.2 Back Surface Temperature of the Sample and Kevlar Fabric Backing. Three layers of Kevlar fabric were placed behind the sample on top of a 100-mm-square and 19-mm-thick horizontal DuPont proprietary polymer block sample holder. In the tests, temperatures were measured at the back surface of the sample and at each layer of Kevlar fabric, as shown in Figure 3.

The measured surface temperatures are shown in Figures 13–20 (data for sample no. 7 are not shown since the thermocouples malfunctioned). Because the polymer block acted as an insulator and retained most of the heat penetrating through the sample blanket, the temperature of the three layers of Kevlar fabric continued to increase, even after the exposure to the front surface of the sample blanket was terminated.

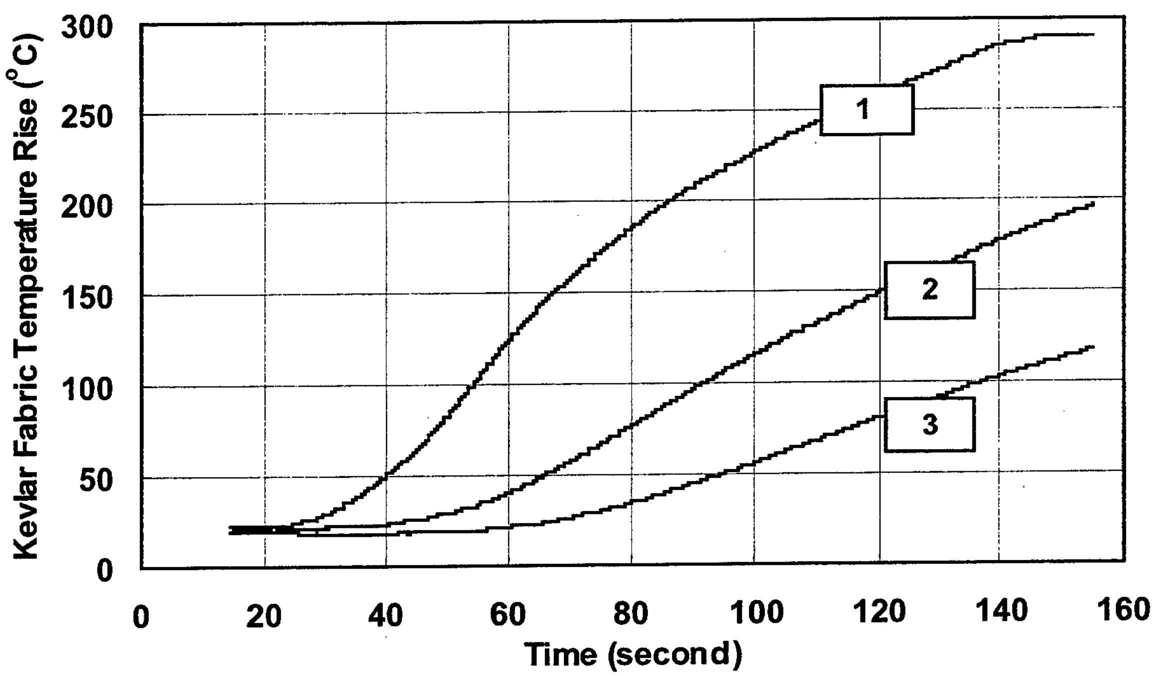

Figure 13. **Back Surface Temperature Above Ambient of Kevlar Fabric Layers 1–3 at the Back of 3-mm-Thick Sample No. 1. Maximum Temperature of the Front Surface of the Sample Is 560 °C.**

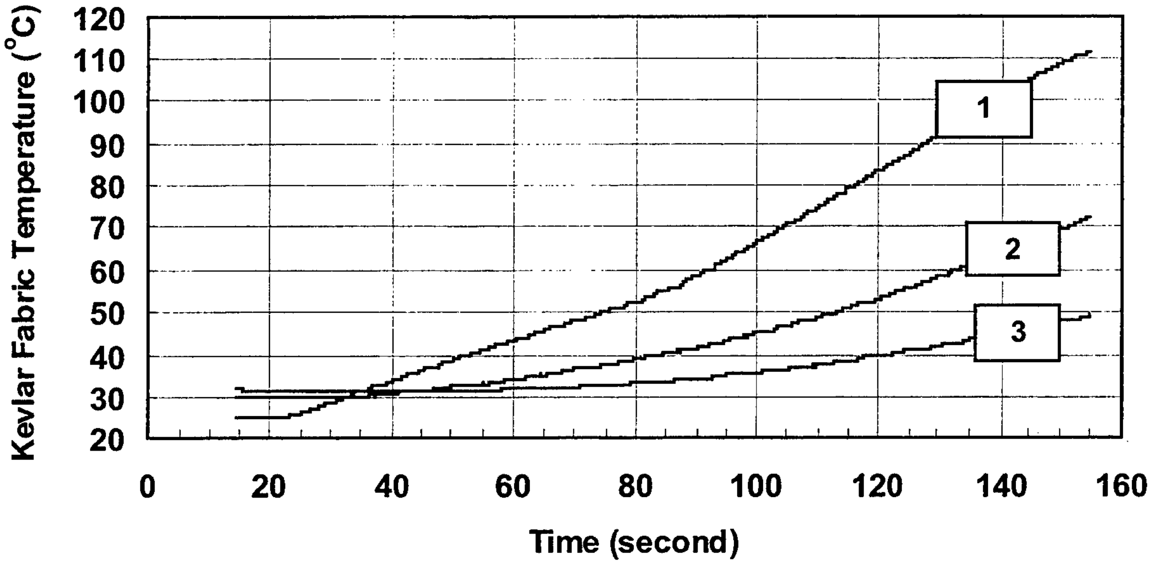

Figure 14. Back Surface Temperature Above Ambient of Kevlar Fabric Layers 1–3 at the Back of 5-mm-Thick Sample No. 2. Maximum Temperature of the Front Surface of the Sample Is 440 °C.

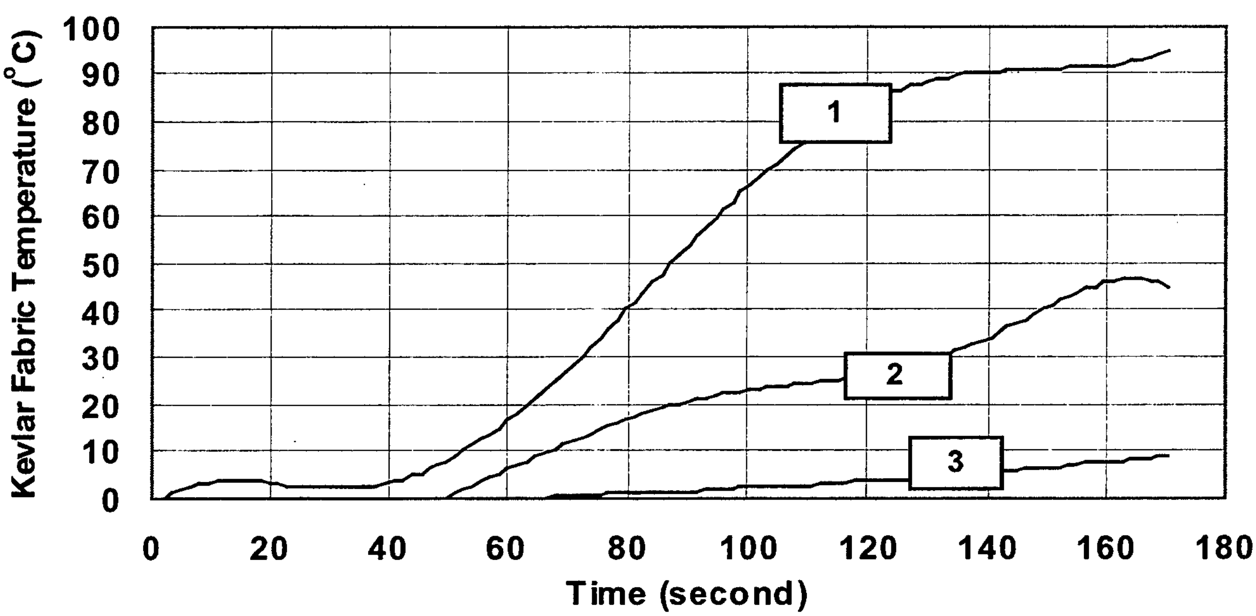

Figure 15. Back Surface Temperature Above Ambient of Kevlar Fabric Layers 1–3 at the Back of 5-mm-Thick Sample No. 3. Maximum Temperature of the Front Surface of the Sample Is 550 °C.

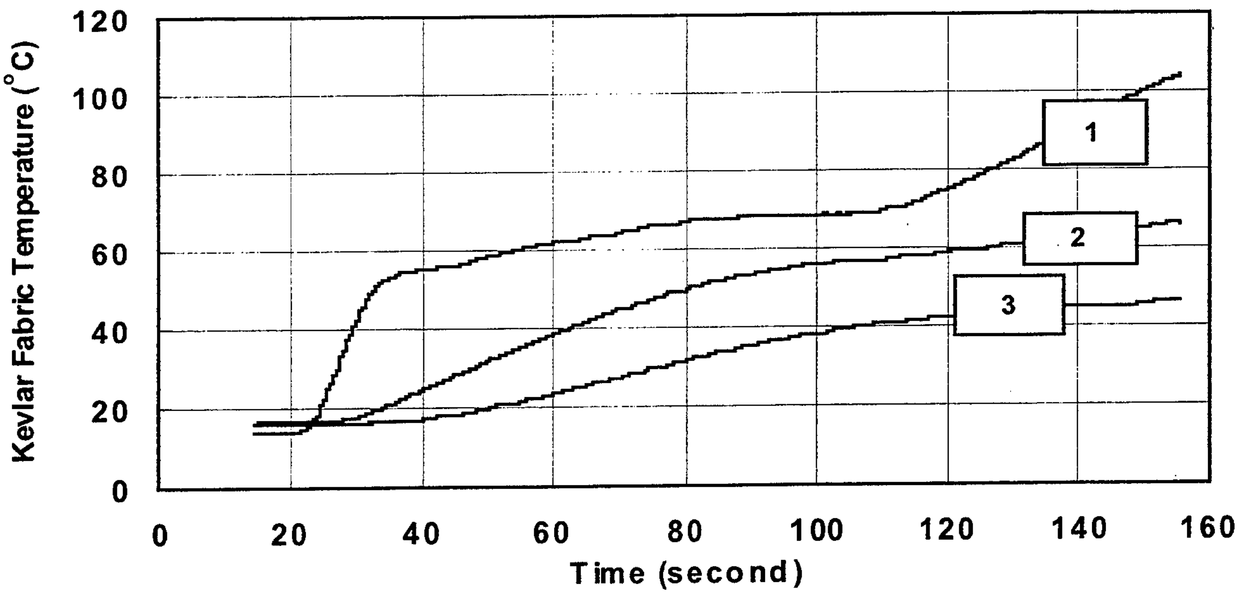

Figure 16. **Back Surface Temperature Above Ambient of Kevlar Fabric Layers 1–3 at the Back of 5-mm-Thick Sample No. 4. Maximum Temperature of the Front Surface of the Sample Is 550 °C.**

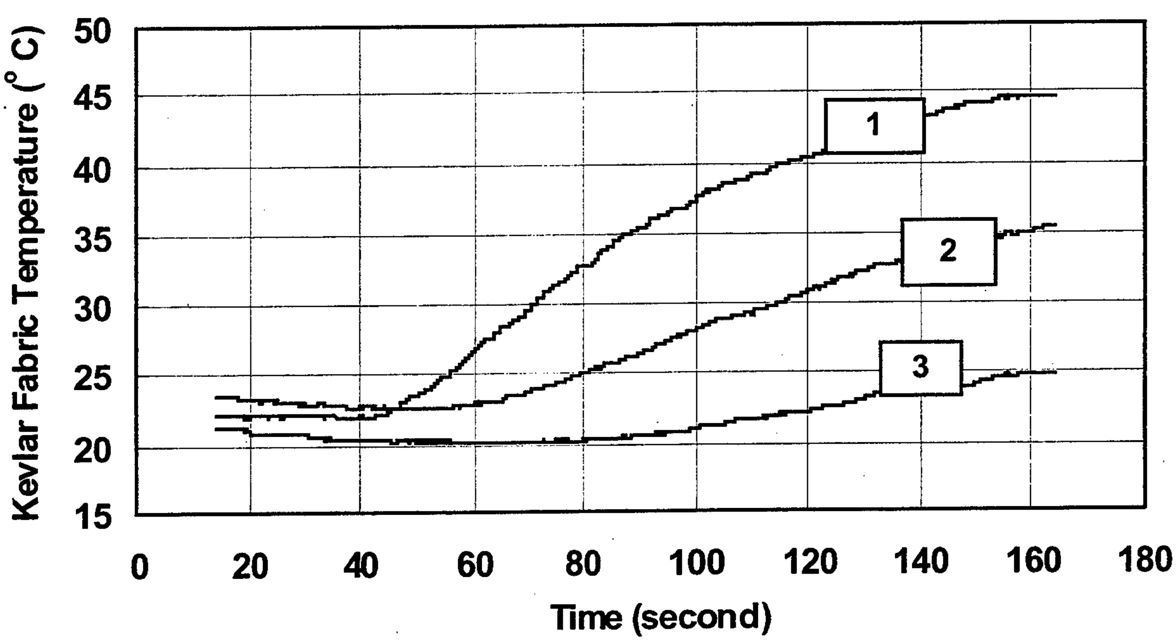

Figure 17. **Back Surface Temperature Above Ambient of Kevlar Fabric Layers 1–3 at the Back of 15-mm-Thick Sample No. 5. Maximum Temperature of the Front Surface of the Sample Is 470 °C.**

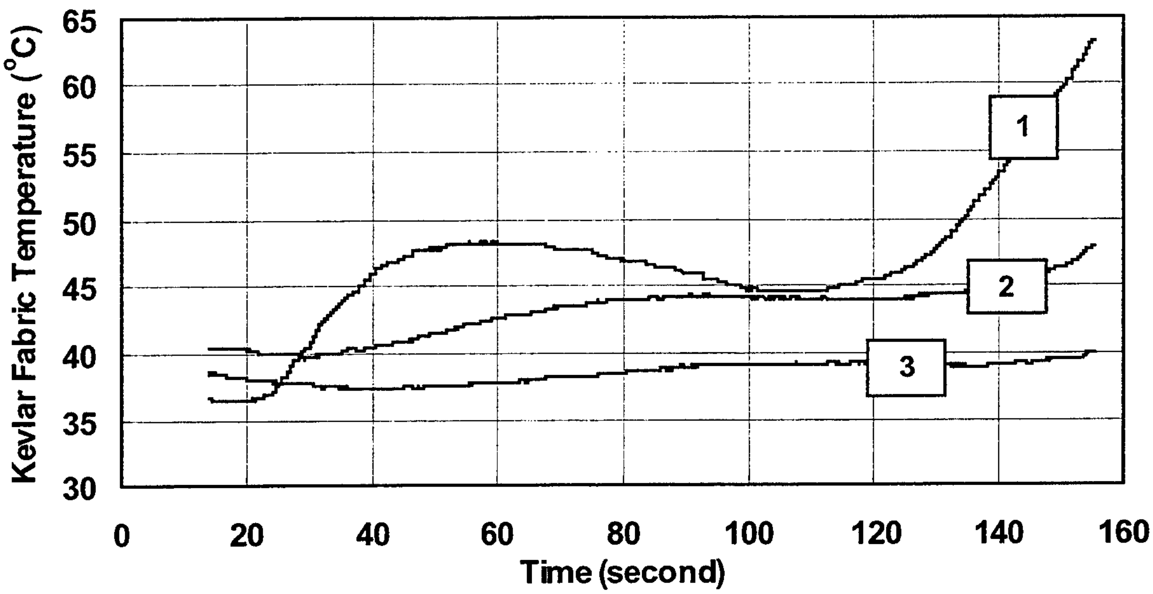

Figure 18. Back Surface Temperature Above Ambient of Kevlar Fabric Layers 1–3 at the Back of 20-mm-Thick Sample No. 6. Maximum Temperature of the Front Surface of the Sample Is 490 °C.

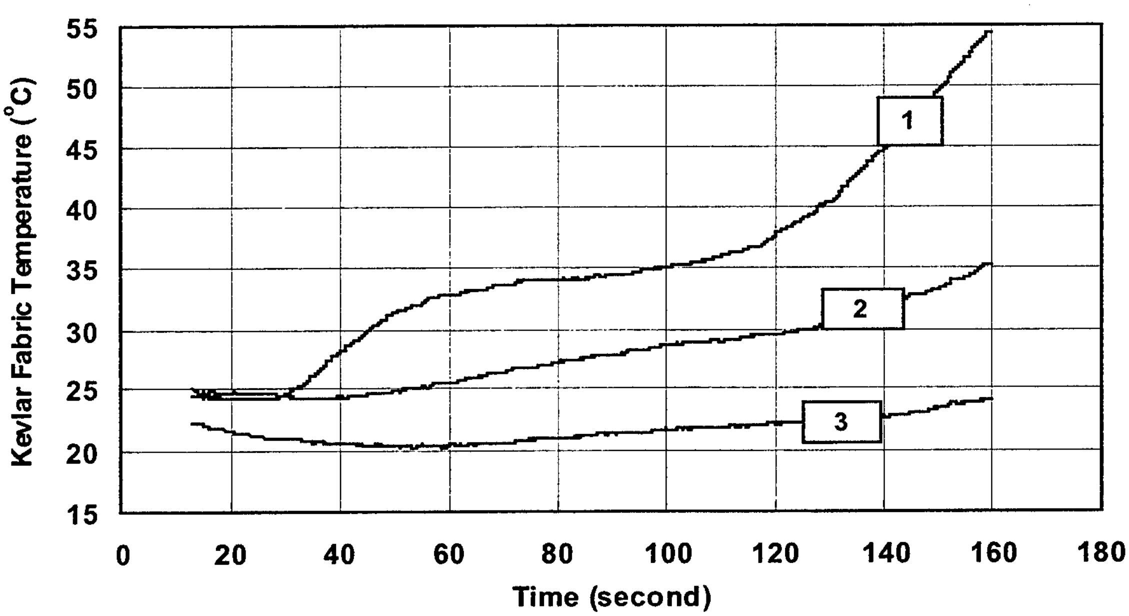

Figure 19. Back Surface Temperature Above Ambient of Kevlar Fabric Layers 1–3 at the Back of 20mm-Thick Sample No. 8. Maximum Temperature of the Front Surface of the Sample Is 444 °C.

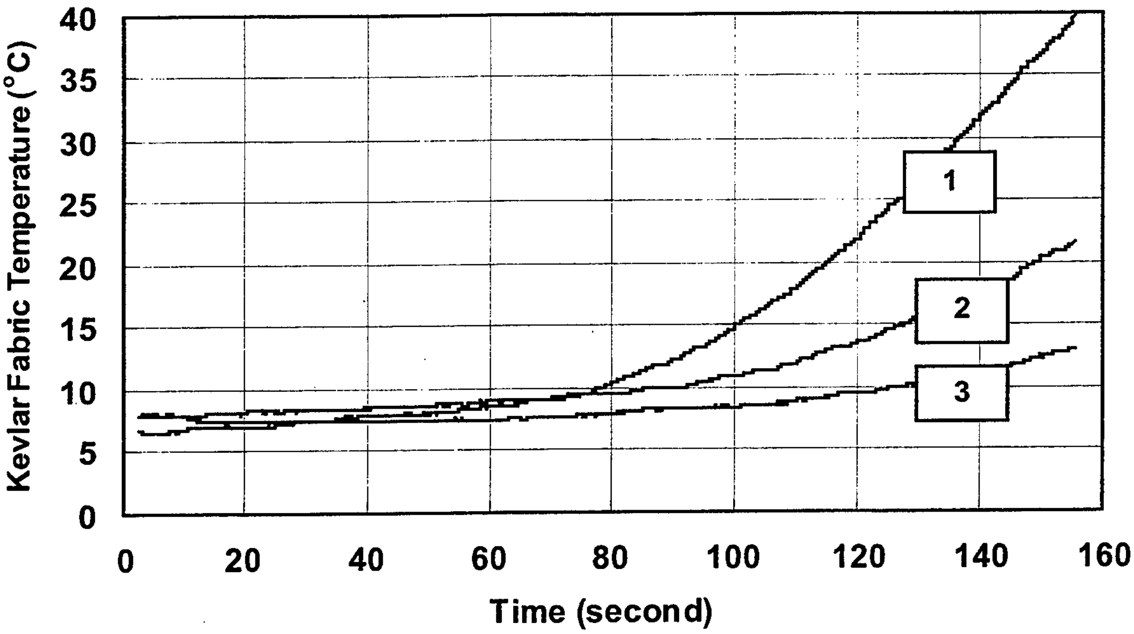

Figure 20. Back Surface Temperature Above Ambient of Kevlar Fabric Layers 1–3 at the Back of 25-mm-Thick Sample No. 9. Maximum Temperature of the Front Surface of the Sample Is 444 °C.

The average back surface temperature of each layer of Kevlar fabric is lower than the average back surface temperature of the sample. The average back surface temperature of the bottom third layer of Kevlar fabric is the lowest, indicating that Kevlar fabric does provide thermal protection, as found in the flame penetration tests (Table 7, combinations of samples #L, #M, and #O). However, it is necessary to use a minimum of three layers of Kevlar fabric.

Table 9 summarizes the maximum temperatures of the front sample surface and temperature rise for the back surface of the third layer of Kevlar fabric. These data indicate that there is a significant decrease in the temperature of the third layer of Kevlar fabric when compared with the front surface temperature of the sample, especially for the thick sample blankets. Thus, to significantly reduce the flame and heat penetration, blankets made of at least 15- to 25-mm-thick layers of inorganic fiber-based fabrics with a minimum of three layers of Kevlar fabrics for backing would be needed.

Table 9. Maximum Temperature of the Front Surface of the Sample and Back Surface of the Third Kevlar Fabric Layer

Sample[a] No.	Fabrics Layers	Thickness (mm)	Temperature above Ambient (°C)	
			Front Sample Surface (Max)	Back Surface of 3rd Kevlar Layer
Thin Sample Blankets				
1	1000/600 aluminum AF – 62 Nextel 1,000/600 aluminum	3	560 (50–60 s)	increasing from 20–110 °C (60–150 s)
2	188 CH; 0.13-in Kaowool paper Rubberized silica	5	440 (40–120 s)	increasing from 30–50 °C (80–150 s)
3	Zetex 10615-1860 0.13-in Kaowool paper 84 GHS	5	550 (50–110 s)	increasing from 3–10 °C (90–170 s)
4	Ceramic fabric 399C-2 0.13-in Ceramic blanket Ceramic Fabric 399C-2	5	550 (50–110 s)	increasing from 20–42 °C (50–150 s)
Thick Sample Blankets				
5	1,000/600 aluminum- Copper knit 500 188 CH	15	470 (40–120s)	increasing from 20–25 °C (80–160 s)
6	1,000/500 stainless steel foil 0.5-in Kaomat 188 CH	20	490 (60–120 s)	increasing from 38–40 °C (60–150 s)
7	1,000/500 OS 0.5-in 607 Superwool 188 CH	20	430 (50–120 s)	fluctuating between 37 and 39 °C (40–150 s)
8	1,000/800 aluminum 0.5-in Kaowool – S 188 CH	20	444 (60–120 s)	increasing from 20–24 °C (60–160 s)
9	1,000/800 stainless steel foil 0.5-in 607 Superwool 1000/600 aluminum	25	440 (10–120 s)	increasing from 10–14 °C (80–150 s)

[a] Same samples as listed in Table 4.

5.3 Resistance to Heat Penetration. As discussed in the background section, the effective thermal diffusivity of a fabric system can be considered as a parameter for expressing resistance to heat penetration. In this study, the effective thermal diffusivity of a fabric system for temperature (T) at a constant heat flux* [14], with absorptivity assumed to be unity was estimated from the following expression:

$$T(x=0) = (2\dot{q}_e''/k)(at/\pi)^{1/2}, \tag{1}$$

where T (x = 0) is the surface temperature (°C), k is the thermal conductivity (kW/m-K), α is the effective thermal diffusivity of the sample (mm^2/s), and t is the exposure time (s). α is expressed as $k/\rho c_p$, where ρ is the density (g/m^3), and c_p is the heat capacity (kJ/g-K). The back surface temperature is expressed as

$$T(x) = (2\dot{q}_e''/k)\left[(\alpha t/\pi)^{1/2} e^{-x^2/4\alpha t} - (x/2)\operatorname{erfc}\left(x/2\sqrt{\alpha t}\right)\right], \tag{2}$$

where x is the thickness of the fabric (m), which was measured for the sample blankets. In the tests, T (x = 0) and T (x) were measured as function of time of the sample. These measured values were used in equations 1 and 2 to solve for k and α. The effective thermal diffusivity values for the sample blankets estimated from this procedure are listed in Table 10. The estimated α values include affects of contact resistance, which were not quantified.

The thermal conductivity (k) values for various fabrics selected for the heat penetration tests are listed in the manufacturers' brochures and range from about 0.5×10^{-4} to 4×10^{-4} kW/m-K. The thermal diffusivity values are generally not listed, except for a few fabrics. For example, the 3M Company has performed heat conduction tests with Nextel 312 fabric in a 2,000 °F (1,093 °C) furnace. The temperature inside the sleeving was measured as a function of time for

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* The expression is used to calculate temperatures inside a material that satisfy the thermally thick condition at various distances from a hot surface, assuming conduction to be the dominant mode of heat transfer [14].

Table 10. Estimated Effective Thermal Diffusivity Values of Sample Blankets

Sample Blanket (Thickness)	Fabrics and Fibers in Layers of the Sample Blanket	Thermal Diffusivity (mm^2/s)
No. 1 (3 mm)	1,000/600 aluminum; AF – 62 Nextel 1000/600 aluminum	nd[a]
No. 2 (5 mm)	188 CH; 0.13-in Kaowool paper; Rubberized silica	0.40
No. 3 (5 mm)	Zetex 10615-1860; 0.13-in Kaowool paper; 84 GHS	0.64
No. 4 (5 mm)	Ceramic fabric 399C-2; 0.13-in Ceramic blanket; Ceramic Fabric 399C-2	0.51
No. 5 (15 mm)	1,000/600 aluminum; copper knit 500; 188 CH	2.66
No. 6 (20 mm)	1,000/500 stainless steel foil; 0.5-in Kaomat; 188 CH	4.25
No. 7 (20 mm)	1,000/500 OS; 0.5-in 607 Superwool; 188 CH	4.13
No. 8 (20 mm)	1,000/800 aluminum; 0.5-in Kaowool – S; 188 CH	5.51
No. 9 (25 mm)	1,000/800 stainless steel foil; 0.5-in 607 Superwool; 1,000/600 aluminum	6.46

[a]nd = not determined due to unsteady front surface temperature (see Figure 7).

1, 3, 6, and 9 layers, and each layer was 0.965 mm. The estimated effective thermal diffusivity values based on the estimation used in this study (equations 1 and 2) range from 0.5 mm^2/s at 120 s to 3.2 mm^2/s at 720 s. The effective thermal diffusivity value at 120 s is comparable to the values listed in Table 1 for similar types of fabrics.

The effective thermal diffusivity values of 15–25-mm-thick sample blankets containing metal fibers range between 2.66 and 6.46 mm^2/s, which are significantly higher than the values for 3–5-mm-thick samples without the metal fibers.

5.4 Estimation of Heat Penetration From Sample Blanket Surfaces Heated to High Temperatures. The heat penetration behavior of sample blankets tested in the study was

examined by the following expression [14] using effective thermal diffusivity values from Table 10, with an assumption that the surfaces were heated to constant high temperatures.

$$\Delta T_b = \Delta T_s \left[\operatorname{erfc}(x/2\sqrt{\alpha t}) \right], \tag{3}$$

where ΔT_b is the steady-state back surface temperature above ambient (°C), ΔT_s is the steady-state front surface temperature above ambient (°C), x is the thickness of the sample (m), and t is the exposure time (s).

To estimate of the back surface temperature from equation 3, the front surface was assumed to be at constant temperatures of 1,000, 2,000, and 3,000 °C for 10, 30, and 60 s. The back surface temperature estimations under these conditions are listed in Table 11. As time increases, the error due to assuming a semi-infinite geometry increases and further validation is necessary.

The back surface temperature estimations for different exposures suggest the following:

- 10-s exposure: the back surface temperature for thin sample blankets (5 mm thick) was in the range of 11–108 °C above ambient. But for thick sample blankets (15–25 mm thick), it was in the range of 0–13 °C above ambient.

- 30-s exposure: the back surface temperature for thin sample blankets (5 mm thick) was in the range of 42–278 °C above ambient. But for thick sample blankets (15–25 mm thick), it was in the range of 3–75 °C above ambient.

- 60-s exposure: the back surface temperature for thin sample blankets (5 mm thick) was in the range of 65–377 °C above ambient, whereas for thick sample blankets (15–25 mm thick), it was in the range of 6–130 °C above ambient.

Table 11. Estimated Back Surface Temperatures of the Third Layer of Kevlar Fabric

Sample Blanket	Temperature Above Ambient (°C)			
	Assumed Front Sample Surface	Third Bottom Kevlar Fabric Layer		
		10-s Exposure	30-s Exposure	60-s Exposure
		ΔT_{k3}	ΔT_{k3}	ΔT_{k3}
No. 2	1,000	11	42	65
$x = 5$ mm	2,000	21	85	130
$\alpha = 0.40\ mm^2/s$	3,000	32	127	195
No. 3	1,000	36	93	126
$x = 5$ mm	2,000	72	186	251
$\alpha = 0.64\ mm^2/s$	3,000	108	278	377
No. 4	1,000	25	79	113
$x = 5$ mm	2,000	51	158	225
$\alpha = 0.51\ mm^2/s$	3,000	76	237	338
No. 5	1,000	4	25	43
$x = 15$ mm	2,000	8	50	86
$\alpha = 2.66\ mm^2/s$	3,000	13	75	129
No. 6	1,000	0	3	6
$x = 20$ mm	2,000	1	7	12
$\alpha = 4.25\ mm^2/s$	3,000	6	18	25
No. 7	1,000	1	9	15
$x = 20$ mm	2,000	2	13	23
$\alpha = 4.13\ mm^2/s$	3,000	3	26	46
No. 8	1,000	1	5	8
$x = 20$ mm	2,000	2	10	17
$\alpha = 5.51\ mm^2/s$	3,000	3	16	25
No. 9	1,000	3	24	43
$x = 25$ mm	2,000	7	48	87
$\alpha = 6.46\ mm^2/s$	3,000	10	72	130

Thus, the back surface temperature for thin sample blankets was consistently higher than the temperature for the thick sample blankets. Therefore, it can be concluded that 15–25-mm-thick sample blankets have higher resistance to heat penetration up to 3,000 °C and up to 60 s than do 5-mm-thick sample blankets. It is possible that under such high temperature exposure conditions, the front/top surfaces of some sample blankets of the multiple-layered fabrics may be damaged due to melting.

The sample blankets had higher resistance to heat and flame penetration and were generically similar to NASA's thermal protection system fabrics for atmospheric entry and hypersonic cruise vehicles (Table 11).

6. Summary

(1) Literature information and flame and heat penetration test data from this study suggest that using a combination of commercially available inorganic (alumina, silica, and ceramic) and organic (Kevlar) fiber-based fabrics in multiple layers are effective in enhancing the resistance of the fabric systems to flame and heat penetration.

(2) Several combinations of the inorganic fiber-based fabrics with three layers of Kevlar fabric backing were used as sample blankets.

(3) Test data from the study suggest that to prevent the back surface of the sample blanket from heating, the front layers of the inorganic fiber-based fabrics need to be 15–25 mm thick, and a minimum of three layers of Kevlar fabric layers need to be used as backing layers. The effectiveness of sample blankets with thickness greater than 5 mm but less than 15 mm can be assessed from the data reported here, since they were not tested.

(4) A procedure has been developed to obtain effective thermal diffusivity of the sample blankets from the measured average steady-state temperatures at the front and back surfaces, thickness, and exposure time duration. The effective thermal diffusivity values of the sample blankets are in good agreement with the literature values for generically similar fabric systems.

(5) Effective thermal diffusivity values of sample blankets provide a useful parameter to estimate their effectiveness in preventing flame and heat penetration to the back of the sample blankets; however, full validation tests are needed.

7. References

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REPORT DOCUMENTATION PAGE

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1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	February 2001	Final, May 1999 - May 2000

4. TITLE AND SUBTITLE
Fire Blankets for Munition Protection: Flame and Heat Blocking Properties of Advanced Materials

5. FUNDING NUMBERS
DAAL 01-97-Q-0276

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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ATTN: AMSRL-WM-MA
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8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-2398

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)
Defence AMMOLOG Activity
ATTN: AMSTA-AR-AL
D. Scarborough, Bldg. 455
Picatinny Arsenal, NJ 07806-5000

10.SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
* Factory Mutual Research Corporation, Norwood, MA 02062

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report examines the flame and heat penetration through layers of fabrics as blankets for thermally protecting stored munitions. Evaluated were 27 fabrics made of inorganic fibers (alumina, silica, and ceramic fibers) and organic fibers (Kevlar, Nomex, and carbon) varying in thickness from 3 to 25 mm.

Two types of tests were performed. First, flame penetration tests were performed with an oxyacetylene flame. Visual observations and measured char depth into a wooden block at the back of the sample were used in the analysis. Second, heat penetration tests were performed in the heat penetration apparatus. A radiant heater was used for heat exposure. Temperatures were measured at the front and back surfaces of the inorganic fabrics and in each layer of the Kevlar fabric. The average steady-state temperatures were used for the analysis.

Effective thermal diffusivity values for the sample "blankets" were estimated from the measured temperatures, sample thickness, and exposure duration using a simple heat conduction relationship for thermally thick materials.

A procedure was developed to obtain effective thermal diffusivity of the sample "blankets" from the measured average steady-state temperatures at the front and back surfaces, thickness, and exposure time duration. This procedure, along with measurements in the heat penetration apparatus, can be used for routinely testing the various types and combinations of inorganic and organic fiber-based fabrics.

14. SUBJECT TERMS
flame penetration, heat penetration, munition protection, fire blankets, effective thermal diffusivity, inorganic/organic fibers

15. NUMBER OF PAGES
47

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

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